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New architecture for high efficiency DC-DC converter dedicated to photovoltaic conversion

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Abstract

The latest researches on photovoltaic energy conversion clearly show that the next generation systems will be both smarter and efficient, with insurance of greater security and modularity. They are clearly oriented nowadays on the multi-point conversion, based on a parallel high voltage bus, with photovoltaic panels owner of their individual Maximum Power Point Tracker (MPPT) connected to an integrated DC-DC converter managing a global Maximum Power Point. This structure allows to avoid shadowing problems. We have studied in this paper the possibility to have a small universal DC-DC converter able to work in a large input voltage range (10 - 40 volts), and producing an output voltage up to around 300 volts with a global efficiency better than 96%. In this paper we describe an original Step-Up converter architecture tested on a standard inverter i.e. including its own MPPT. We also discuss the possibility to use high voltage parallel bus to improve the electro-magnetic compatibility and electro-magnetic pulse robustness by the low surface of wirer loops, which also represents an interesting way to decrease wiring prices. The global efficiency improvement of this architecture has been estimated for +15 to 20% compared to classic ones. This structure allows the use of numerous technologies (amorphous, poly, mono... cells) working together on a single HVDC bus in an optimal efficiency. Finally, it is possible to migrate sequentially and progressively from an old standard technology towards this new one as described before.

Keywords: DC/DC converters Photovoltaic HVDC MOSFET

1. Introduction: Multipoint conversion

The smart power converter is one of the power management systems for photovoltaic generator, which currently presents a real interest as shown in various recent communications [1][2][3]. It was shown that the main advantages of such a parallel multi-point system structure is the high efficiency, specially in case of mismatches or lighting defects between panels or else, permanent or temporary default on a panel. The goal of such a structure is to create a total Independence between all the photovoltaic (PV) modules and to possibly avoid all mismatch problems. In this way we report in the Fig.1 the possibility to have a global system based on a small PV installation composed by about 20 panels. In this study, we consider DC-DC converters sizing for the conversion of the electrical power delivered by PV panels and connected to a DC load, which can be an inverter or simply a passive load working at high voltage. As shown in Fig.1, the suggested solution in this study is based on an individually drive of the energy delivered by each photovoltaic panel with a single DC-DC converter connected at the output to a common HVDC bus. In order to insure the voltages needed to a direct connexion to the HVDC bus, we realized high efficiency converters operating at output voltages up to 300V. Considering that the converting ratio is about 8 this application reveals a technical challenge.

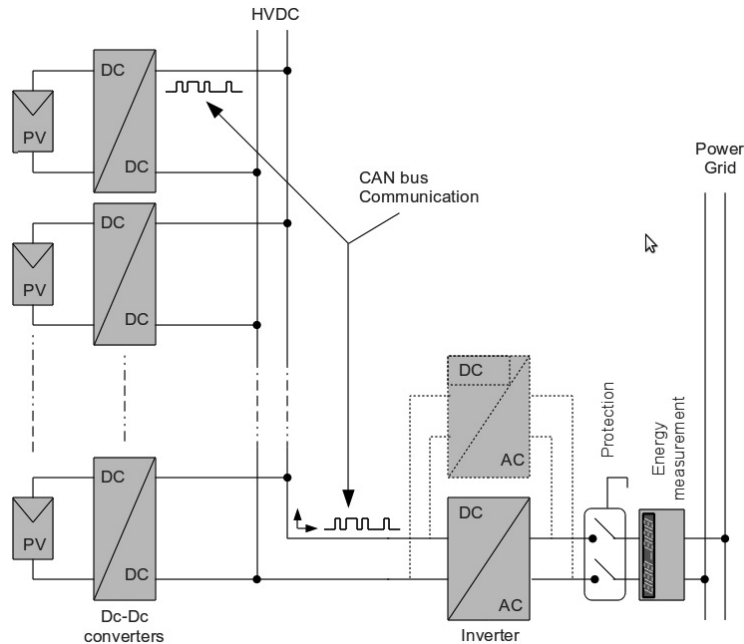


Figure 1: Global structure of a HVDC parallel bus is more advantageous in case of shadowing mismatches and multiple technologies.

For that we suggest an architecture of the individual converters, as presented in this paper, based on a magnetically coupled coils boost. Some publications related to similar structures named "High efficiency DC-DC converters" [4][5], confirm the choice of only one switch element for panel power conversion. It allows a very small integrated configuration on a board placed at the rear of the PV panel. The very low number of components is a security against failures and increases the MTBF (Mean Time Before Failure). Usually, one admits that the energy conversion have to be done with a global losses below 15%, including the connexions and cables losses. So, in our estimations, we can consider that a efficient smart distributed converter as we propose, should not exceed 10%, to be an interesting improvement way.

In this publication, to point out the advantages of the magnetically coupled coils boost, we first present classical boost used in PV applications and analyze the various origin of losses, and finally we suggest to improve the efficiency of this new system by integration of a recovery stage.

2. Classical boost analysis

The basic boost converter is a very good approach to understand where optimizations have to be done to insure a high efficiency conversion of a PV generator. We have analyzed all parts of a basic Step-Up boost converter to point out the localization where main sources of losses occur. For that, we have modeled the Step-Up converter by the schema reported the schematics in Fig.2. In this representation D1 is the free wheeling recovery diode, L1 is the energy recovery inductor and Q1 is the power MOSFET.

To analyze this basic system configuration, we have considered a typical input voltage in the 12 - 40VDC range, which corresponds to standard voltages delivered by PV panels, and an output voltage around 300VDC, so including standard voltage level used by the most common distributive electrical network.

2.1. Losses in the MOSFET

It has been established [6] that when a MOSFET is used as switch, its losses drastically increase with the voltage that it controls. The simulation of the behavior of MOSFETs switching high voltages as been modeled and referred in a previous publication, for various MOSFET families [6].

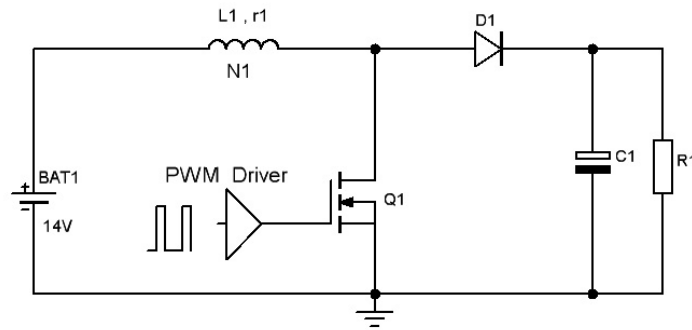


Figure 2: Basic boost.

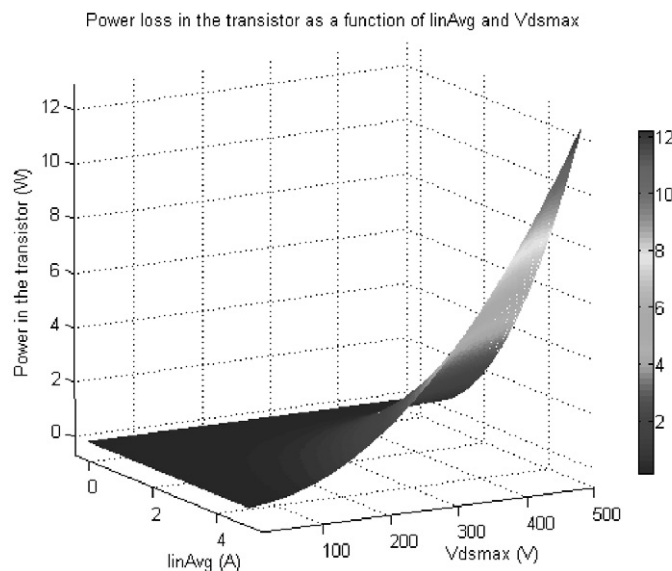


Figure 3: Losses in the switching MOSFET for increasing voltage ratings transistors.

We report, for a self-coherent analysis, in Fig.3, the total losses in the MOSFET family 2N72..-2N73.. as a function of V_{dsmax} and I_{inAvg} , which are the maximum of the output voltage and the average switching current, respectively. This curve can be fitted with a second order equation, pointed out the nonlinear increase of R_{dson} with the maximum voltage rating. We can define a coefficient α , with $\alpha > 1$, yielding to the equation: $R_{dson} = R_0 + (V_{dsmax})^\alpha$. This equation, based on the analysis of various MOSFET families [6], shows that MOSFETs can be used for an efficient boost, i.e. with an acceptable efficiency, only in the low voltage range, for $V_{dsmax} < 100...150V$.

2.2. Losses in the inductor

The inductor represents another large origin of losses. Fortunately the method for losses estimation in a inductor is well known [7][8][9]. There is a linear dependency between the frequency of signals applied to the inductor and its volume, and then it is interesting to operate at high frequencies to minimize the size of the inductor. Indeed, this implies that the inductor used for the switching converters, like in boosts, must have a good behavior in the high frequency range and for high currents. Thus, a first improvement, in comparison with standard inductors, can be considered using special materials for the ferrite, and studying an air-gap free geometry. However, with a functioning point at high frequency, the losses in the inductor will increase in the magnetic material but also in the wires due to the skin effect.

2.3. Losses in the recovery diode

The characteristics and the efficiency of the recovery diode is important because it is located at the output stage of the circuit by where all power is transferred to the load. So this component has to be a fast diode, i.e. with a very small switch time and able to work at high voltage. For the converters built in the framework of the present study, we have chosen a new model of silicon-carbide diode especially adapted for switching integrated regulators. The recovery time of such diodes is very short and makes their use possible for frequencies up to 100kHz .

Within the experimental input and output voltages conditions, as fixed above, the maximum efficiency that we have obtained with this classical boost was around 85%. In the 15% global losses of the converters, more than 10% are due to the MOSFET that has a high value of $R_{ds(on)}$ in the high voltage range, as pointed out in Fig. 3.

3. Magnetically coupled coils boost

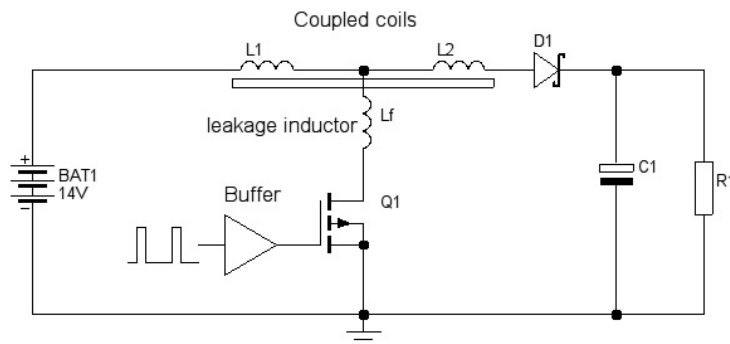


Figure 4: Magnetically coupled coils boost.

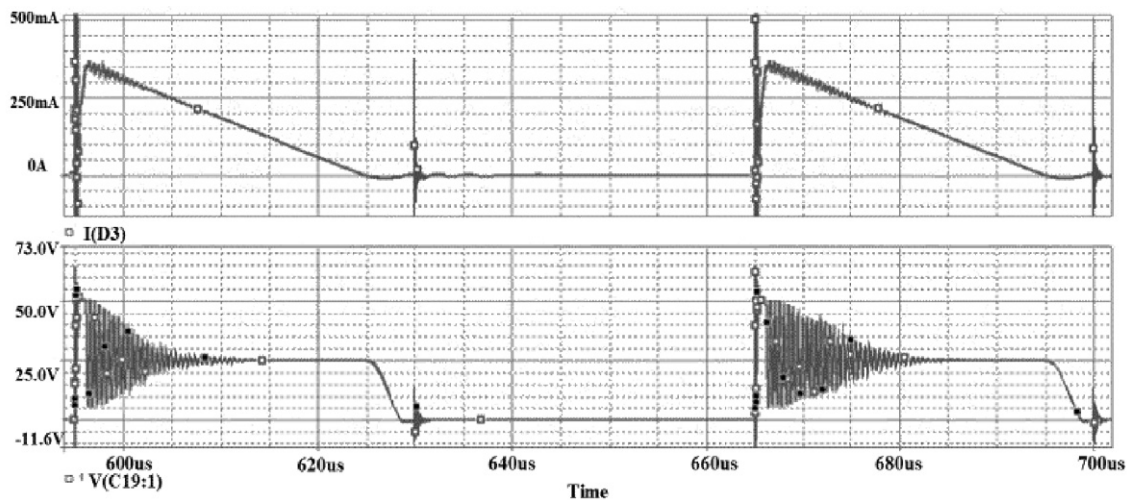


Figure 5: Simulation of the output current and MOSFET drain voltage of the magnetically coupled coils boost.

The analysis presented above points out the fact that the MOSFET is the main limitation, degrading the efficiency when the converter is designed to work in the 300V range, and it obviously appears, Fig.3 that the efficiency of the overall system will increase when the voltage in the MOSFET will be reduced. In this way, we suggest to balance the voltage on the MOSFET and the output, using an autotransformer which can, by a suitable transformation ratio,

boost the output voltage while guaranteeing a low voltage on the MOSFET drain. The schema of the circuit of the magnetically coupled coils boost is shown in Fig.4. We have also reported on this schema the leakage inductor $L3$ in serial with the MOSFET that produces some over-voltages at switch off time. The increases of the input current depends on the input voltage and the L_1 value, and the decreases L_2 current depends on L_1 magnetically coupled with L_2 . The ratio between I_1 and I_2 at the MOSFET switch off follows the Eq.1.

$$\frac{I_1}{I_2} = \frac{(N_1 + N_2)}{N_1} \quad (1)$$

By else, the number of turns N_1 and N_2 of L_1 and L_2 , respectively have a direct incidence on the duty cycle of the switching as shown in Fig.5.

The behavior of this converter has been simulated in Fig.5 in which we report the shape of the output current and V_{ds} . In these two graph, we have a duty cycle about 50% and we can notice the over-voltage due to L_f at the beginning of the cycle.

4. Improvement of the magnetically coupled coils boost

We have shown above that the over-voltage due to the energy stored in the leakage inductor (see Fig.4) deteriorates the efficiency of the converter. This energy must be stored and recycled into an intermediate stage. In standard PV applications, this stage has to work at a medium voltage about 50VDC for a 15VDC panel, and at 80VDC for a 40VDC panel. Two practical solutions can be proposed to convert this power.

The first solution to be considered is based on the injection of the converted current in the primary stage. The circuit for such a solution is illustrated in Fig.6, where we can notice the recovery stage followed by the buck conversion stage. $D2$ and $C2$ form the energy storage stage delivered by the leakage inductor, L_f , whereas in the buck conversion stage, the energy is transferred by a switch in series with $L3$ and $D4$; $D3$ is the freewheeling diode. This architecture is well adapted for high voltage output and low coupling coefficient for the coupled coils. Nevertheless, this system, due to its complexity, brings a non-negligible cost compare to the cost of an individual panel and a lower reliability.

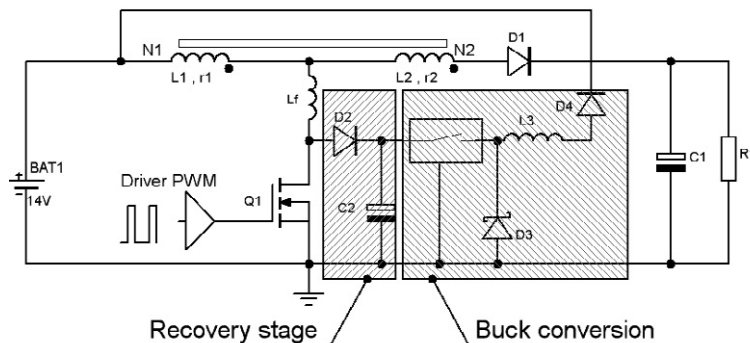


Figure 6: Magnetically coupled coils boost with recovery at the input.

For improvement of the reliability and, additionally to decrease the cost, we suggest a circuit based on the injection of the converted current in the secondary stage. The circuit for such a solution is illustrated in Fig.7. We can note that this system looks like a traditional boost succeeded by a coupled coiled Booster stage.

In this arrangement, we insert in series at the middle point of the coupled coils a diode $D1$ insuring a transfer of the main energy and allowing the storage of the recovery energy in the leakage inductor in $L1$. This configuration eliminates over-voltage by recovering the stored energy which cannot be magnetically transferred into the output stage. This solution is available only in the case of a high coupling coefficient for the coupled coils, which is possible in case of medium voltage as in PV applications. It is to be of note that some simulations, not represented here, done on Orcad have confirmed two critical points, i.e. 1) the possibility to adjust the pulse width modulation duty cycle of the MOSFET relatively to the transformer ratio and the voltages applied to the converter, and 2) the immunity of this concept for various coupled factor between the coils of the transformer.

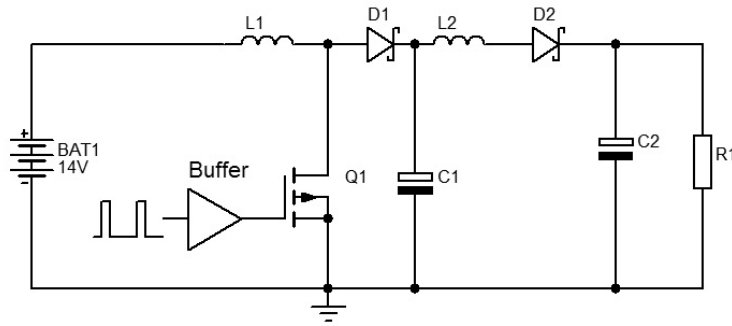


Figure 7: SMagnetically coupled coils boost with recovery at the output.

5. Implementation

We have implemented this boost system dedicated for the photovoltaic conversion and placed behind a PV panel. The picture of Fig. 8 shows the realization. It is to be of note that the MOSFET control is not discussed in the above analysis. In our system, it is based on a dedicated MOS buffer and a microcontroller computing the PWM signal applied to the buffer input. We easily recognize the coupled coil and the MOSFET (LTC1443). The LCD display allows the live control of the system parameter. Thus, this circuit has allowed the conversion of the photovoltaic energy, under 40VDC in an output voltage up to 600VDC with an efficiency reaching 96%. As we can also see in the picture Fig.8, the converter is driven by a micro-controller which can instantaneously evaluate the PV Maximum Power Point.

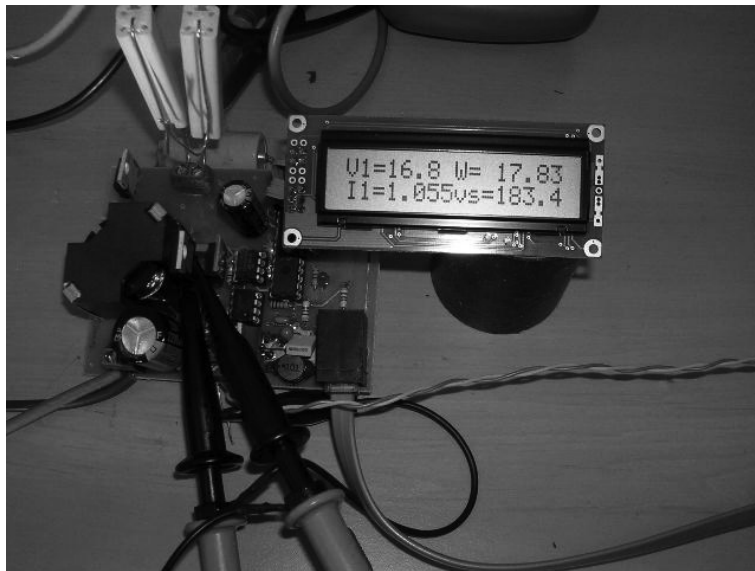


Figure 8: Implementation of a prototype of coupled coil recovery boost under tests.

The management of the converter behavior when it is connected to HVDC parallel bus of the inverter has to take into account the tracking routine of the inverter which is based on the determination of an extrema in the P-V characteristic curve. So it cannot find a MPP and, as a consequence, it cannot deliver a constant power as a function of the output and an error will occur. To solve this problem we degrade the response of the local converter to insure a maximum of the PV individual power at the more efficiency voltage. This is done by the local computing power which insures a smooth variation decreasing the provided power to the inverter to bring a global stability around an optimal previous value for the output converter voltage. This optimal value is given by the manufacturer of the inverter.

We experiment this converter prototype to convert energy issued from a single PV panel and deliver an output voltage up to 300VDC. With such a system, placed behind an individual PV panel, we have obtain an efficiency of 98.6% for an output power equal to 58W under an output voltage equal to 180V. Finally, an installation has been tested including a string of four photovoltaic panels added with their individual magnetically coupled coils boosts with recovery stage. The output of the boosts are connected in parallel and constitute the main bus. The global efficiency considering the PV energy and the energy injected in the bus reaches 98%.

6. Conclusion

We have analyzed the main origins of losses in classical boosts used in PV generator. We have shown that the MOSFET used as switch induces a drastic increase of Joule losses with the increase of the voltage, mainly responsible of the huge deterioration of the efficiency of the all system. We have shown, in our simulation and practical experiments that a magnetically coupled coils boost balances the voltage applied to the MOSFET with the delivered voltage allowing, when a judicious number of turns ratio is respected in the coils, the integration of a low $R_{ds(on)}$ MOSFET. Finally, to avoid the over voltage due to the leakage inductor, we proposed to add to the earlier converter a recovery stage recycling this voltage directly to the output. With such a system, placed behind an individual PV panel, we have obtain an efficiency of 98.6% for an output power equal to 58W under an output voltage equal to 180V. An installation has been successfully tested including a string of four photovoltaic panels constituting the main bus.

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References

- [1] S. Vighetti, Systèmes photovoltaïques raccordés au réseau : Choix et dimensionnement des étages de conversion, Ph.D. thesis, Ecole Doctorale "Electrotechnique Electronique Automatique et Traitement du Signal" (septembre 2010).
- [2] J. M.G.Villalva, E.R.Filho, Comprehensive approach to modeling and simulation of photovoltaic arrays, IEEE Transactions on Power Electronics 24 (2009) n4, pp.1198–1208.
- [3] T. Oozeki, Advanced analysis of shading effect using minutely based measured data for pv systems, Tokyo University of Agriculture, Shanghai China, 2005.
- [4] M. G. Kim, Boost converter using an energy reproducing snubber circuit (May 1997).
- [5] L. Qun-Zhao, High-efficiency, high step-up dc–dc converters, IEEE Transactions of power electronics 18 n1 (2003) 1–9.
- [6] Y. Xiong, Modeling and analysis of power mosfets for high frequency dc-dc converters, Ph.D. thesis, College of Engineering and Computer Science University of Central Florida Orlando, Florida (2008).
- [7] M.-H. H. Dwight, Proximity effect in wires, mutual inductance of filamentary circles, mutual inductance of two thin disk coils, magnetic field from round coil of small rectangular cross section, in electrical coils and conductors, McGraw-Hill, Inc., New York (1946) pp 192–292.
- [8] F. T. J. Bhagwan, Mutual inductances of coils on a cylinder of infinite length IEEE Trans. Magnetics, 16, 2 (1980) pp 477–479.
- [9] M. SFG98, Soft Ferrites a user's guide, Magnetic Materials Producers Association, 1998.